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SENSING CHALLENGES FOR CONTROLS AND PHM IN THE HOSTILE OPERATING CONDITIONS OF MODERN TURBINE ENGINE (POSTPRINT)

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Structures and Controls Branch
Turbine Engine Division

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14. ABSTRACT
Advanced gas turbine engines have evolved over the last several decades to dominate aviation's propulsion, commercial and the military market. Continuing engine performance and reliability advances will require sensor components that operate reliably under extreme engine operating conditions (e.g., takeoff, max thrust) and in harsh environments (e.g., high temperature and radiation). The design of advanced controls and Propulsion Health Management (PHM) will also depend on the use of components with increased susceptibility to atmospheric radiation. This paper will discuss the current and future engine operating temperature environment that provides major challenges in sensor design for control and propulsion health management. Atmospheric radiation effects on the design and operation of engine electronics and PHM systems will be discussed. Methods to mitigate deleterious effects on system safety and performance will also be discussed. Finally, expected changes in the engine operating conditions over the next several decades will be discussed along with solutions for sensing and control.

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Sensing Challenges for Controls and PHM in the Hostile Operating Conditions of Modern Turbine Engine

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Advanced gas turbine engines have evolved over the last several decades to dominate aviation's propulsion, commercial and the military market. Continuing engine performance and reliability advances will require sensor components that operate reliably under extreme engine operating conditions (e.g., takeoff, max thrust) and in harsh environments (e.g., high temperature and radiation). The design of advanced controls and Propulsion Health Management (PHM) will also depend on the use of components with increased susceptibility to atmospheric radiation. This paper will discuss the current and future engine operating temperature environment that provides major challenges in sensor design for control and propulsion health management. Atmospheric radiation effects on the design and operation of engine electronics and PHM systems will be discussed. Methods to mitigate deleterious effects on system safety and performance will also be discussed. Finally, expected changes in the engine operating conditions over the next several decades will be discussed along with solutions for sensing and control.

I. Introduction

A. Role of Gas Turbine Instrumentation and Engine Control

In the engine test cell, instrumentation and control sensors are used for engine diagnosis and prognosis. In a safety-critical flight environment, sensing and control have to be robust and durable to function reliably in the harsh environment that exists in the turbine engine. Accurate real-time control requires careful placement of instrumentation to provide accurate real-time measurements for processing by the Full Authority Digital Engine Control (FADEC). The frequency and bandwidth capability of sensors for engine control are drastically different for each sensor type.

The turbine engine fuel control system is comprised of temperature recirculation valves, metering valve, and pump bypass valve. The fuel metering valve assembly is responsive to electrical signals generated by the FADEC in response to sensors that measure turbine speed, pressure, temperature and operator thrust request. The fuel bypass valve redirects un-metered (excess) fuel from the area of the fuel metering valve assembly to an area of low pressure fuel. The amount of fuel flowing through the fuel bypass valve is controlled by two separate actuation systems. The first actuation system includes a compressor discharge pressure sensing system and responds to a rise in the compressor discharge pressure by decreasing the bypass fuel flow.

The other system responds to changes in the differential in pressures by opening a bypass valve in order to achieve a rate of metered fuel flow that is appropriate for the compressor discharge pressure. Feedback and temperature sensors required for control must operate at the maximum of either the fuel or compartment temperatures. Future robust control techniques will impose additional requirements of high response and operation in close proximity to the measured phenomenon.

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The turbine engine gas path control employs variable geometry features for efficient operation. Compressor vanes and the nozzle assembly within the engine are opened and closed in response to engine operating parameters. Additionally, parameter ranges, limits and restrictions are set by the turbine engine control. Geometry control requires closed loop position feedback sensors for each of the actuators.

Eliminating the life-reducing effects of high-cycle fatigue (HCF), combustion instabilities, compressor surge, and combustion instability control will require the use of sensors with high temperature tolerance and high frequency response. This requirement cannot be met by currently available technology. As a result, current and planned technology development programs are working to develop accurate, high frequency sensors capable of operating in harsh environments. The need for accurate high-temperature dynamic pressure measurements is an integral step to the implementation of active surge control methodologies. For high frequency applications, it is generally necessary to reduce the distance from the sensor to the environment to a minimum.

Typical aerospace pressure transducers are limited to about 500° F, while in today's large gas turbine engines, compressor exit temperatures can be on the order of 1200 to 1400° F, meaning that current pressure transducers are not sufficient for measuring these conditions. The normal technique used to handle this temperature environment is to cool the transducer or locate the transducer in a benign environment.

B. Role of Gas turbine Controls and Sensors

The cost of turbine engine controls can be nearly 20% of the total cost of the engine, but may contribute up to 40% to the total life cycle cost due to the high number of maintenance actions required[11]. Because the expected service life of commercial engines is as much as 80,000 hours, and the expected operating environment of military engines is extreme, development of high temperature sensors and controls are appropriate technologies to meet future performance goals of turbine engines and reduce their maintenance cost.

Modern turbines have FADECs that provide safe and stable engine operation. These FADECs govern and limit operation of the combustion system. To minimize emissions of carbon-monoxide and nitric-oxides (NOx), and ensure design life, combustion systems may include control scheduling algorithms that receive input measurements of the exhaust temperature of the turbine and the actual compressor operating pressure ratio.

In a turbine engine control system, the fuel control uses a fuel metering valve assembly that is responsive to electrical signals generated by the FADEC. The FADEC response depends on sensors that measure turbine speed, pressure, and temperature, indicative of the operator thrust request. A fuel bypass valves provides a means for returning excess (unmetered) fuel from the main pump to the inlet low pressure supply. Sensors are also required to measure compressor discharge pressure for operating bypass valves to control pressure fluctuations. A high response sensor is needed to measure differential pressure for controlling the main fuel metering valve to achieve a rate of metered fuel flow corresponding to compressor discharge pressure. Figure 1 shows the high temperature regimes for the sensors needed for future aerospace applications.

The future challenges for turbine engine sensors and controls are implementation of specific technologies for diagnostics, stability management, and reconfiguration for damage tolerance as shown in Figure 2. These challenges includes tip clearance control, active combustion control, data fusion, integration of the turbine engine with the flight control, and high frequency analysis for turbine engine controls. These technologies will prolong the life the engine, increase reliability, as well as reduce Life-cycle cost. In all techniques, the objective is to reduce engine wear and tear and obtain maximum life from the components.

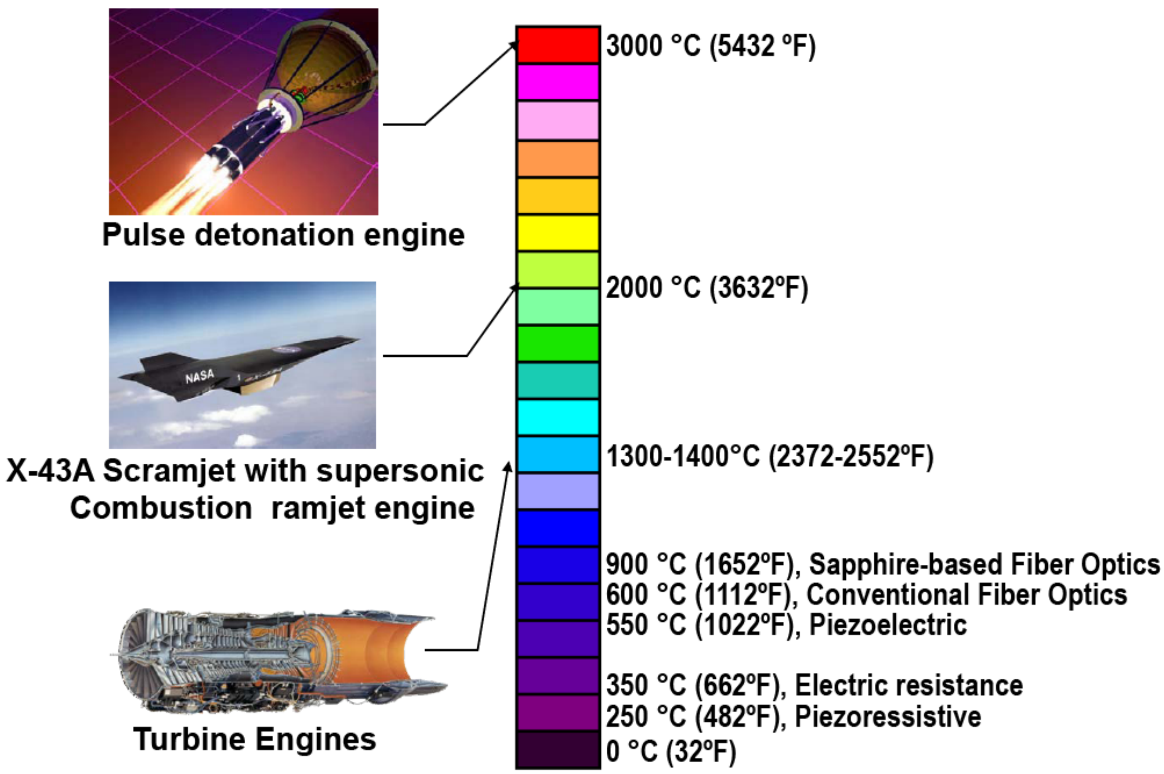

Figure 1. High Temperature Regimes for Sensors with Aerospace applications.

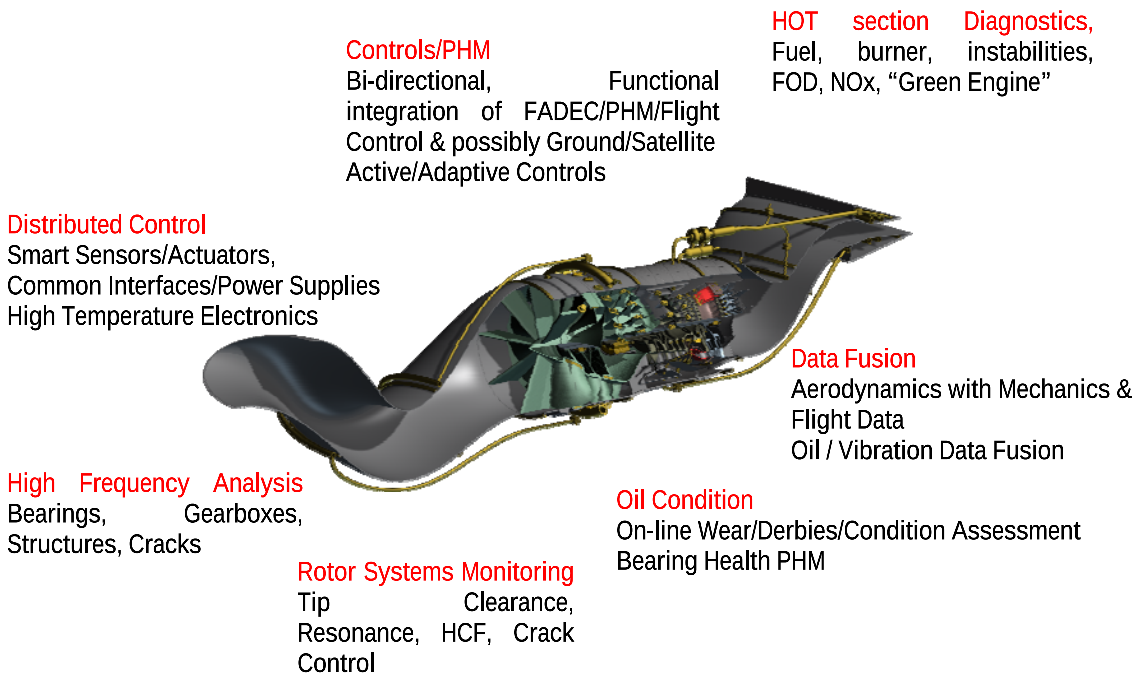

Figure 2. Future Engine Challenges.

II. Sensor Challenges

Three primary challenges prevent new sensor technology from evolving, maturing and transitioning to implementation on a propulsion engine. They are technical, system, and market driven forces. Technical challenges include developing the materials and device technology to accommodate the engine operating environment. High vibration and temperature are the major issues that limit applications. System challenges have to do with the ability to design a sensor technology to work with an existing architecture and accommodate a particular weight and volume constraint. System challenges also include meeting reliability and maintainability goals. Market driven challenges require finding innovative ways to make high temperature sensors cost effective. These include having the sensor provide multiple parameters, reduced failure rates, and critical component diagnostic data.

A. Technical Issues

To accommodate the harsh environmental conditions required for engine PHM and control measurements, the most significant technical challenges faced are designing and packaging[8] sensor technology using both advanced high temperature and engineered materials. They include emerging optical, piezoelectric, and semiconductor materials. They may be employed in MEMS[9] (Micro Electrical Mechanical Systems), MOMS (Micro Optical Mechanical Systems), fiber, and thin film configurations. Specific high temperature sensor issues include hysteresis, parameter drift, chemical stability and life. Packaging, mounting, and wiring are technical challenges[7] that occur during implementation that will reduce performance and impose restrictions on operating temperature, pressure and location.

B. System Design Issues

To accommodate the engine system environment, high temperature sensor technology must interface with existing and planned engine interface and communication architectures as well as meet the size and egress requirements at the measurement location. Numerous formats and standards exist that define voltage levels and data communication protocols for state-of-the-art (SOA) sensor transmission. Progresses in developing standards for smart sensors, wireless and high speed aerospace data bus communication are also occurring. However, high temperature sensors pose unique problems in interface design due to their specialized mode of operation. For example, use of wavelength division multiplexed (optical), radio frequency (RF), and other high bandwidth formats will require dedicated instrumentation and processing that is not likely to be encompassed by efforts to standardize aerospace sensor interfaces and communication.

C. Market Driven Challenges

The number of controlled and measured variables on both military and commercial turbine engines has been increasing with each new generation of engine and have stabilized over the recent past. However, to meet increasing demand for capability to reduce maintenance cost and increase life of turbine components, use of increased diagnostics and material stress or damage measurements will be required. Many of these measurements will be made in extreme temperature environments. The cost of high temperature sensor technology for aerospace applications will be higher than the current SOA. However, potential use in emerging commercial applications can mitigate the expected high cost of advanced materials and new designs.

III. Critical Sensor Needs

Key engine sensors are those that provide measurements to monitor, update, and validate the engine state. These measurements ensure safe turbine operation and prevent in-flight shutdown, unless there are serious multiple failures in the system. Engine control measurements include temperatures and pressure at strategically selected stations in the engine. Displacement, vibration, speed, and other parameters are also used to provide component feedback, loop control, limit control, and structural health. Many non-measurable performance parameters are also calculated, such as thrust, stall margin noise, and emissions, depending on the engine original equipment manufacturer (OEM). Fig. 3 illustrates The Locations for Sensors for Control of a typical Turbine Engine Today.

Component temperature limits are listed in for two different applications. These are listed in Tables 1 and Table 2.

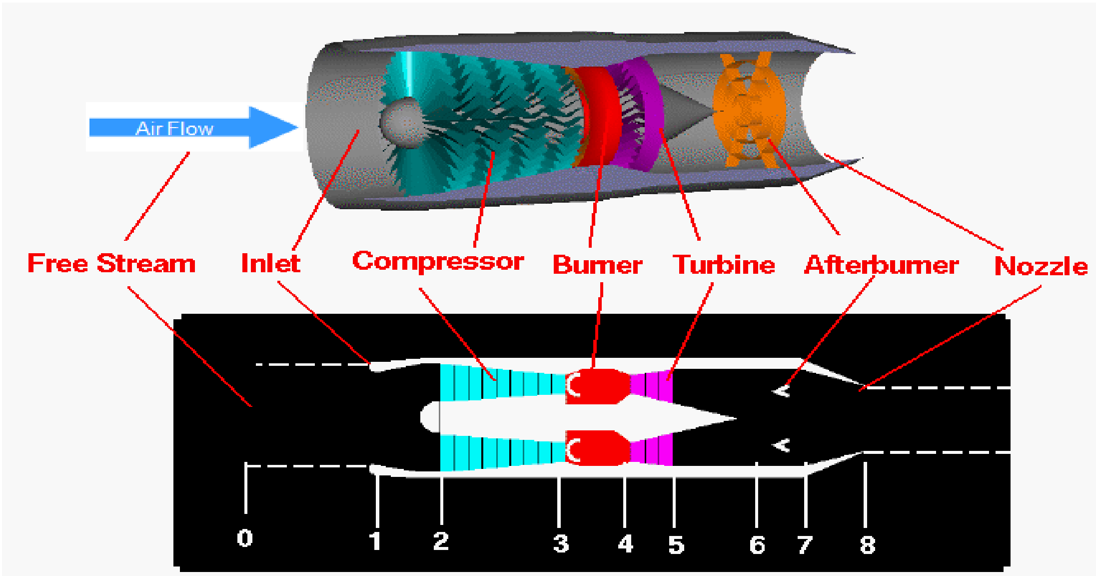

Figure 3. The Locations for Sensors for Control of the Turbine Engine Today.

Table l. Legacy Turbine Engine Sensor Requirements†

Measured Parameter Sensor Location	Parameter Range	Required Accuracy	Environment	Response
Pressure (total): Compressor Inlet	0 to 50 psi	± .2% full scale	Temperatures up to 400°F*	10-20 ms
Pressure (total): Compressor Discharge	0 to 500 psi§	± .2% full scale	Temperatures up to 500°F*	10-20 ms
Pressure: Combustor	25 to 500 psi	± 4 psi	Temperatures up to 2400°F*	10-20 ms
Temperature: Compressor Inlet	-65 to 500°F	±3°F	-65 to 500°F	3 to 5 sec. time Constant (typical)
Temperature: Combustor Outlet	500 to 2400°F	± 10°F	-65 to 2400°F	1.8sec. time constant (typical)
Temperature: Turbine Outlet	500 to 1500°F	0.75% point (°C)	-65 to 1500°F	0.7 to 1 sec. time constant (typical)
Temperature: Turbine Blade	1000 to 2000°F	±18°F	-65 to 2000°F	10 ms
Fuel Flow: Gas Generator	200 to 20000 lb/hr 1" to 1.5" lines	±1.5% full scale	-65 to 400°F 1000 to 1200 psi	<2 ms
Fuel Flow: Augmenter	100 to 400000 lb/hr 1" to 1.25" lines	±1.5% full scale	-65 to 400°F 1000 to 1200 psi	<2 ms
Angular Speed: HP, LP Rotor Speed	1500 to 20000 RPM	±3 RPM		
Linear Position: Actuators	.5 to 8.0 inches	±1.5% full scale	-65 to 600°F	<2 ms
Rotary Position: Inlet Guide Vanes, Variable Stator Vanes	60° range of motion	±1°	-65 to 600°F	<2 ms
Shaft Torque	-2000 to 6500 ft. lbs.	±0.5% point	2500 to 12000 RPM -65 to 900°F	-

†Turbojet, Turbofan, and Turboprop Engines in Service Today[15]

Note: All values listed are for reference only and may not be applicable for a specific Application.

*Transducer location dependent §Could be higher

Table ll. ADVANCED TURBINE ENGINE SENSOR REQUIREMENTS‡

Measured Parameter Sensor Location	Parameter Range	Required Accuracy	Environment	Response
Pressure (total): Compressor Inlet	0 to 120 psi	± .2% full scale	Temperatures up to 1200°F*	10-20 ms
Pressure (total): Compressor Discharge	0 to 500 psi§	± .2% full scale	Temperatures up to 1200°F*	10-20 ms
Pressure: Combustor	25 to 500 psi	± 4 psi	Temperatures up to 3300°F*	10-20 ms
Temperature: Compressor Inlet	-65 to 1200°F	±3°F	-65 to 1200°F	3 to 5 sec. time constant ¥
Temperature: Combustor Outlet	500 to 3300°F	± 10°F	-65 to 3300°F	1.8sec. time constant (typical)£
Temperature: Turbine Outlet	500 to 1500°F	1% (F°)	-65 to 1500°F	0.7 to 1 sec. time constant (typical)£
Temperature: Turbine Blade	1000 to 2200°F	±18°F	-65 to 2200°F	10 µs
Fuel Flow: Gas Generator	Up to 34000 lb/hr (PPH)	±1.5% full scale	-65 to 800°F 1000 to 1200 psi	<2 ms
Fuel Flow: Augmenter	Up to 62000 lb/hr (PPH)	±1.5% full scale	-65 to 800°F 1000 to 1200 psi	<2 ms
Angular Speed: HP, LP Rotor Speed	1500 to 20000 RPM	±3 RPM		
Linear Position: Actuators	.5 to 8.0 inches	±1.5% full scale	-65 to 800°F	<2 ms
Rotary Position: Inlet Guide Vanes, Variable Stator Vanes	60° range of motion	±1°	-65 to 800°F	<2 ms
Shaft Torque	2000 to 6500 ft. lbs.	±0.5% point	-65 to 900°F 2500 to 16500 RPM	<10 ms
Blade Tip Clearance	.010-.020 inches	0.001 inch	1600°F Turbine	1 to 2 µs
Inlet Distortion Sensor(s)	Psi, ft/sec, flow angle	<0.1 psi	-55 to 150°F	>50 Khz
Fuel Density/Heat Content	Lb, Btu/lb	0.5%	-55 to 350°F	10 ms
Air Mass Flow	Lb/hr	<0.5%	-55 to 150°F Inlet	10 ms

‡Next Generation Advanced Turbojet and Turbofan Engines[15]

Note: All values listed are for reference only and may not be applicable for a specific Application.

§ Could be higher

*Transducer location dependent

£ Desire to reduce response time

¥ Response ≤ 1 sec. desirable

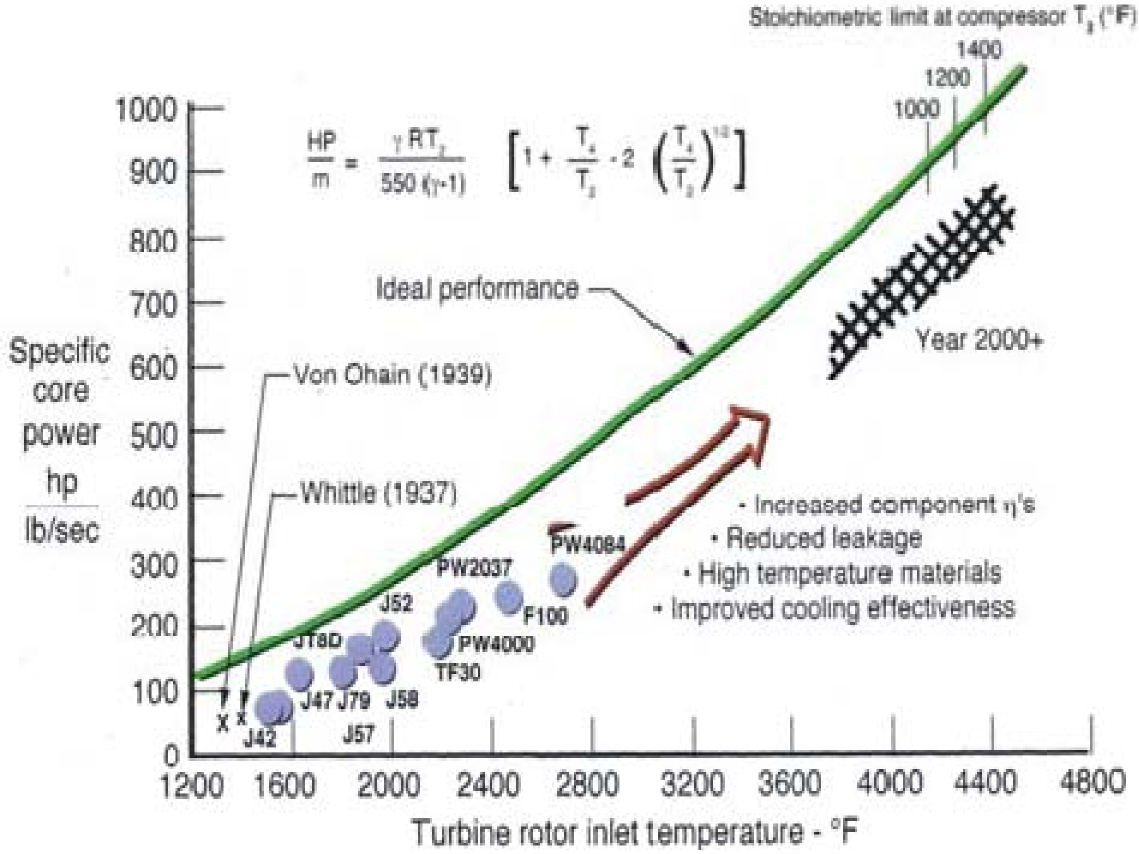

Figure 4. Evolution of Turbine Engine Performance.

For control purposes, the highest temperature measurement required is around 4000° F[13], but for future applications a range of 4200- 4400° F is desired (see Fig. 4). Alternative ways currently used to cope with high temperature employ measurements taken at adjacent locations that are exposed to lower temperatures.

Attaining higher operating temperatures in the turbine engine will result in achieving both a greater thermodynamic efficiency and increased power output per unit of engine weight. Turbine engines should operate ideally with stoichiometric combustion in order to achieve greatest efficiency. However, the temperatures resulting from stoichiometric and even near-stoichiometric combustion are beyond the endurance capabilities of metallic turbine engine components. Progress has been made in cooling schemes and use of nickel-based "super alloys" to allow rotating components to operate at higher temperatures. Ceramic components offer increased ability to operate un-cooled when compared with metals. They have been used in research engines to achieve higher operating temperatures. These improvements have resulted in higher temperature requirements for sensors measuring combustion parameters. In defining the sensor needs for combustor one has to find the best location to measure the temperature. Fig. 5 shows a can-annular combustor for turbine engine. There is still ongoing research to find the best location to place these sensors for control of pattern factor.

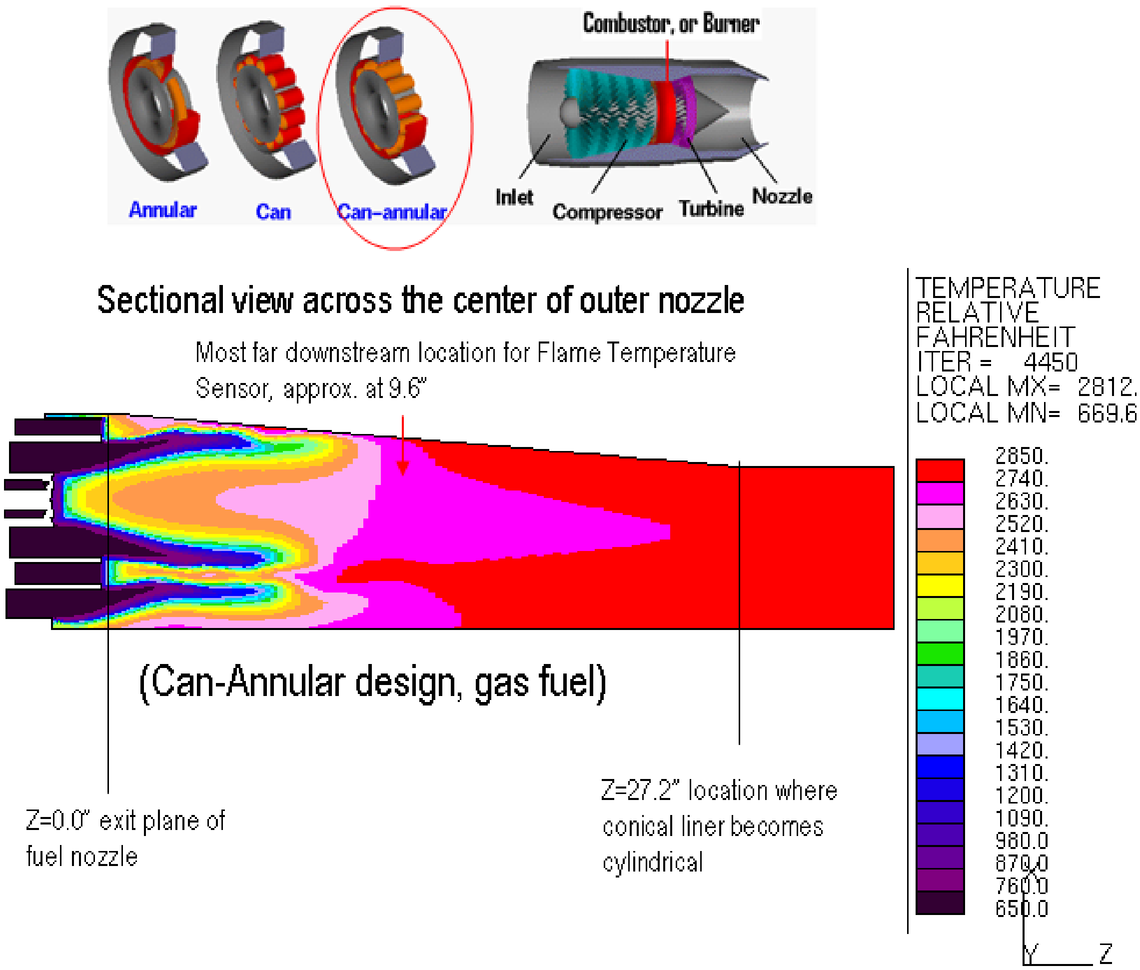

Figure 5. Temperature Distribution in the Combustor.

IV. Future Engine Environment

A. High Temperature

Future turbine engines will be designed for improved engine efficiency and performance by increasing engine pressure ratio, combustion temperature [13], reducing compressor bleed flows, and use of increased mechanical power extraction. Fig. 4 shows the potential for increased power extraction with rotor inlet temperature (RIT). Engine station temperatures are related to pressure ratio and combustion temperature, as shown in Fig. 5. As station temperatures rise, engine components, accessories, and sensors must be designed to accommodate the increasingly harsh case, nacelle and gas temperature environment. . Figure 3 shows the location of the sensors used for control purposes. The engine OEMs, sensor, and controls manufacturers need to work closely to integrate the new capability on the engine.

Pyrometers are typically used to measure turbine blade metal temperatures. However, they can be designed as passive optical light guides or gas path probes. Packaging considerations limit their operational mounting temperature to 900˚F. They are fabricated with high temperature optical materials such as Sapphire, Alumina, and YAG that have melting points between 3500˚F and 3,700˚F. They have been successfully used to measure temperatures (passively) up to 5800˚F. Disadvantages of pyrometry in the turbine section are the potential for lens fouling and need for engine case access.

Optical instrumentation can be employed to measure many low and high temperature parameters. Past experience has shown that the chief limitation to implementing high reliability optical sensors is surviving the vibration environment and development of a durable connection and distribution system. State of the art measurement probes can operate up to 3,000 ˚F.

Thermocouples are used almost universally in every temperature measurement application. They are constructed of parallel conductive wires of dissimilar materials bonded at one end, and generate a voltage due to the Seebeck effect. They are available with continuous measurement capability from – 270˚F to 2,300˚F. Platinum-Rhodium Type R and S thermocouples have a maximum useful measurement range to 3,000˚F. while specialized C-types can go as high as 4,000˚F.

Turbine tip clearance sensors based on measuring capacitance, eddy current, and microwave energy have primarily been used for instrumenting test engines. Eddy Current sensors have been demonstrated to operate at 1000˚F while capacitive clearance probes are available that operate at 1,500˚ F. These sensors can be costly and have limited reliability in the engine environment. Microwave sensors offer the potential for higher temperature operation and ability to non-intrusively measure clearance, vibration, and speed parameters at many locations in the engine as shown in Fig. 3 and 6. Their operation is based on measuring the relative impedance or reflection coefficient at the blade –to- case interface. These sensors may be fabricated with a high temperature ceramics compatible with the engine case materials. Processing the data can be accomplished at a benign engine location.

RF sensors include a variety of electromagnetic sensing and transmission concepts including eddy current sensors. Current devices are passive and are limited by the maximum temperature capability of component technology, such as thin film resistors and ceramic capacitors. Magnetic induction coils have also been constructed that can operate up to 1,300˚ F. Research in very high curie temperature piezoelectric materials for surface acoustic wave (SAW) devices, novel semiconductor materials, and plasma sprayed thin film structures offers potential for high temperature active RF sensors.

Pressure sensors are available based on inductive, capacitive, and piezoelectric properties. For high precision aerospace applications, the silicon semiconductor strain gauge pressure sensor is widely used. They can operate at high temperatures (1150˚F), are durable and can withstand vibration levels up to 200 gs. Their small size and wide operating bandwidth provide much flexibility for measuring dynamic pressure at either low or high temperature stations (figure 5) in the turbine engine.

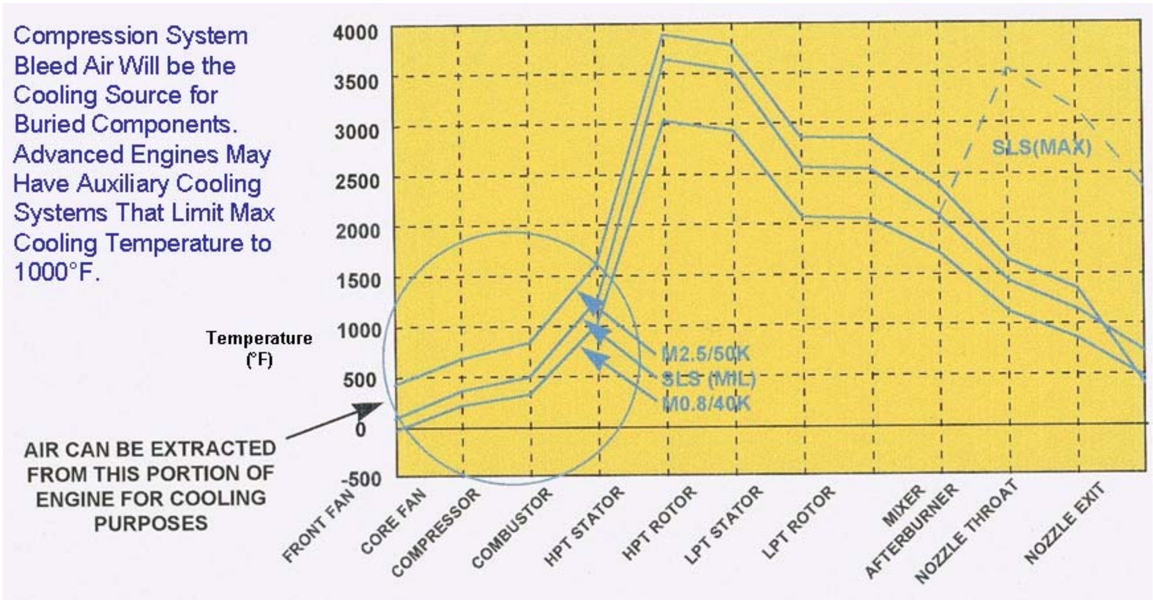

Figure 6. Internal Components of a Turbine Engine Temperature Profile.

V. Effect of Radiation

A. Internal/External Electromagnetic Radiation Environment

The effects of most electromagnetic interference disturbances (EMI) on electronic devices and sensor electronics is well understood[4] and can potentially be accommodated by design[5]. These sources include atmospheric generated lightening or man-made emanations from signal transmission and electrical machinery. Disturbances from high energy sources, such as EMP, are sources of high effective radiated power. Their characterization and effects on electronics are incompletely understood. They have high potential to induce undesirable effects such as soft errors or component failure. Because the sensor element is exposed to this environment, it becomes the primary conduction path for the propagation and effects of these disturbances.

The evolution of wireless and networked monitoring technology presents two issues with regard to EMI accommodation, operation in the environment and its effect on other components.

B. Ionizing Radiation Environment on Sensors and Electronics

The deleterious effects on sensor electronics due to cosmic particle radiation in the atmosphere and during major solar particle events have become an increasingly important safety and dependability issue since the first reports and study[3] of in-flight occurrences in early 1996. The effects of these so-called single event upsets are attributed to high energy neutrons and protons[2]. The FADEC, electronics, sensing, and actuation systems are exposed to atmospheric cosmic particle radiation effects via single event effects. These particle events are very hard to predict and their effect on aircraft is difficult to calculate. These effects on electronics assume that the aircraft is operating at high altitudes under 60,000 feet (18,288 m). Redundancy and error detection are methodologies to accommodate those effects within turbine engine control system, including FADEC and electronics. There are also design and fabrication guidelines intended to help aerospace equipment manufacturers standardize their approach to single event effects control systems and electronics that can withstand the damaging effects of cosmic radiation on entire systems

Atmospheric neutrons from cosmic rays are the cause of Single Event Upsets in flight computers on board commercial and military aircraft. The evidence shows that the numbers of these neutrons increase with aircraft altitude as does the number of SEU events. These kinds of events can also be seen at ground level in tests of computer memory. SEUs due to 100 mev neutrons occurring in FPGA memory[1] will cause a 'reconfiguration' every 8 hours ($1.3X10^{-6}$ errors per flight hour) while SEUs in unprotected devices at altitude have an SEU rate of $2.8x10^{-5}$ per flight hour. In commercial avionics which includes turbine control systems, about 20% of all 'Could Not Duplicate' events are caused by SEUs". The terms Single-Event Effects (SEE) are disturbances in an electronic device caused by a single energetic particle such as a neutron or proton striking a transistor in a memory cell. As an example, they can take several forms, but most commonly appear as transient pulses in logic or bit flips (changing logic '1' to logic '0' or vice versa) in memory cells. Some effects are soft failures (recoverable) but others can cause permanent damage to or even destruction of a device. SEE are of particular concern to the aerospace world because the neutron flux at normal aircraft cruising altitudes can be hundreds of times greater than at sea or ground level, where the vast majority of devices now are expected and designed to function. Furthermore, the continuing trend to smaller, denser, faster and more power-efficient integrated circuits and field-programmable gate arrays (FPGAs) actually increases the devices susceptibility to SEE. This is because the lower transistor voltages in these newer devices mean that the threshold at which the ionizing field charge from a single energetic particle may cause an error is also lower. Additionally, there is more effective area to influence. However, the effects of SEE are device dependent and can vary significantly depending on geometry.

VI. Sensors in Active Control Systems

A. Sensors for Active Clearance Control

To improve turbine engine performance and efficiency, active clearance control of the high pressure turbine (HPT) can be employed. This technique, applied to axial flow gas turbines controls the radial clearance between the tips of the rotating blades and the surrounding annular shroud[6]. By reducing the blade tip to shroud clearance, designers can reduce the quantity of turbine working fluid which bypasses the blades, thereby increasing engine power output and efficiency at all conditions. Increased turbine efficiencies (up to 5%) can be achieved by using a closed loop actuation system that precisely controls clearances at rates sufficient to handle the engine thermal dynamics and provide optimal clearances during cruise.

Although such systems have been investigated for many years, all of the systems have lacked a tip clearance sensor able to survive in the turbine environment. These conditions require sensors and actuators that can survive high temperature and vibration environment with high reliability. Several companies are developing a tip clearance sensor using microwave and optics technology that has shown promise for providing precise blade clearance information within the HPT. In the microwave technique, the sensor measures distance by comparing the received and transmitted signal. These sensors must be able to survive the high temperature environment to function properly.

In passive techniques, active clearance control can be employed by controlling the clearance with a quantity of working fluid that regulates the temperature of certain engine structures, thereby controlling the blade tip to shroud clearance as a result of the thermal expansion. In such a technique, cooling air flow may be switched or modulated in response to various engine, aircraft, or environmental parameters.

To improve engine system life and reduce the levels of emissions, smoothing the combustion pattern factor at the combustor exit can be performed. It is also possible to extend the stability domain by reducing the potential for oscillation (instability) induced by coupling between resonance modes and combustion. These techniques are considered Active Combustion Control (ACC). ACC technique can be employed by providing feedback-based control of the fuel injection, the fuel-air mixing process, or staging of fuel sources. They can also provide flexibility (additional margin) during the combustor design process. In developing ACC technology, there are a number of technical challenges that must be addressed. These challenges include developing temperature, emissions, and pressure sensors that can survive in the harsh environment near the combustor.

VII. Summary

This paper described different types of sensors for engine controls and health management in harsh turbine engine environment. These sensors must be capable of measuring temperature, acceleration, pressure, and strain at high temperatures, high-g forces, and in the presence of environmental radiation and corrosive and erosive media. It is important to emphasize that sensor performance in these extreme environments is made possible by using an integrated modular technology applied to harsh environments for 1) electronics, 2) sensor structures , 3) packaging that possesses the requisite, unique material properties to survive such harsh environments with compatible encapsulation, and 4) radiation hardened components and electronics. In advanced turbine engines, the control designers are increasingly interested in monitoring the performance of systems in harsh environments for stability and fuel saving issues. Implementing active controls requires cost-effective clearance, temperature, and pressure sensors that are robust enough to survive the combustion process or hot engine location. Both optical and microwave technologies are being developed to accommodate these measurement requirements. Development of new materials and micro-fabrication techniques is progressing to enable fabrication of radio frequency (RF) sensors for wireless turbine engine instrumentation in high temperature locations. Future advanced engines will also require control systems with highly integrated electronic circuits, faster processors, and higher bandwidths to accommodate new sensor measurement capability. At the same time the push toward increasing miniaturization is being driven by size and weight limitations and strict reliability requirements. The result is an increasing heat flux at both the component and circuit board levels the sensors will be operating. The contractors are increasingly needed to be aware in designing components that will be able to survive these conditions.

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